Wireless medical information system network for patient ECG monitoring

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Abstract

The emergence of telemedicine developments and the implementation of wireless networks in the medical field has paved the way for research into how we can best harness wireless technology to provide the medical sector with robust, accurate and 'usable' solutions. This paper describes the implementation of a Medical Information System Network that allows medical instrumentation data to be accessed and controlled by handheld devices operated by medical practitioners. Embedded platforms are used for the Medical Information Nodes that communicate with ECG instruments. We explore and compare the performance of implementing real-time acquisition of Patient ECG signals on an FPGA with a software implementation. It was found that the ECG module implemented as custom logic occupied a smaller percentage of the CPU time and also consumed less current than the software implementation.

1. Introduction

Recently there have been many advances in telemedicine and patient monitoring due to the development and usage of wireless networks and mobile systems. The use of wireless networks and mobile devices in hospital and other medical environments has the potential to improve resource management, reduce costs, time and improve overall patient care. Medical environments can place large demands on the robustness and reliability of wireless communications systems because real-time information can be used to make critical decisions about patient care. Wireless networks are in use in hospitals to provide a network infrastructure for administration clerical work but are not used for direct patient monitoring. Instruments for patient monitoring of vital human measurements are usually not networked and so cannot be controlled or monitored remotely. The main advantages of having networked instruments are that the recordings can be organized in a central database which can be accessed rapidly at any time and location. We propose and have implemented a Medical Information System Network (MISN) that allows Electrocardiogram (ECG) instruments to be connected to and controlled via an Ethernet network. The MISN also allows ECG instruments to be controlled by authorized mobile devices.

As highlighted by [2], in many health care institutions patient records are still being recorded and distributed in paper form. Measurement recordings of instruments such as ECG and body images are still recorded and transferred in physical formats such as paper and photographs. There are standards for electronic ECG patient records and electronic instrument recordings such as the Standard Communications Protocol (SCP) [4] and the ISO/ IEEE 11073-30300. There are few common file formats such as SCP that are used to record instrument readings and patient details. Unfortunately, those file formats tend to not utilize existing text and image formats for recordings and hence require special readers for viewing. The MISN system records ECG recordings in a widely used Graphics format which can be opened by most common image viewers and web browsers.

In this paper, we present the implementation of an integrated patient ECG monitoring and administration architecture using mobile computing devices. Our system, the medical information system network (MISN) consists of medical information nodes (MINs) connected to a central server via Ethernet. Each MIN has an ECG acquisition module that controls and receives data from an ECG instrument. The MIN can be controlled via a web interface or by using a mobile (cellular) phone or other Bluetooth-capable Mobile Computing Device (MCD). The MIN uses a Bluetooth link to communicate with the Mobile phone. Bluetooth

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was chosen as the transfer medium due to its wide spread usage on mobile computing devices (MCD) such as Personal Digital Assistants and mobile phones. This fact, coupled with the user profiles of Bluetooth communications that provide serial port interfaces and the short range of Bluetooth, allows the MIN to be controlled within the near vicinity and by a variety of devices. The use of Bluetooth security options also ensures that only authorized devices can access and control the instrument. An ECG Instrument communications protocol was also developed to overcome the limitations of varying Bluetooth capabilities across a range of MCDs.

The MIN is a Field Programmable Gate Array (FPGA)-based embedded system platform that uses the Microblaze softcore processor from Xilinx running the uClinux operating system. An advantage of using a uClinux based system is the availability of open source code for a variety of software functions such as web and Ethernet connections. This allows the MIN to connect to a conventional Ethernet network. The ECG signal acquisition module was implemented in digital logic on the FPGA. The advantages of using an FPGA is that time critical operations such as ECG signal acquisition, can be implemented using custom digital logic. As shown in this paper, this can reduce the overall processor usage and power consumption of the Microblaze processor.

This paper is organized into seven sections. Section 2 presents a review of background and related work. Section 3 is an overview on the operation of the MISN infrastructure. Section 4 discusses the hardware and software module implementations of the MIN. Section 5 discusses the digital logic and processing requirements of the MIN. Future areas of investigation are discussed in section 6 and conclusions are drawn in section 7**.**

2. Background and Related Work

The concept of delivering ECG information wirelessly to handheld devices used by medical practitioners or patient relatives has had some attention in recent literature. Hung and Zhang [5] report on an implementation of a WAP-based telemedicine system for monitoring patient signals. Specifically, ECG and blood pressure information are used in their work. The patient's signals are recorded, sent wirelessly via RF to an indoor receiver station and processed and stored in a PC-based database. This database is accessible by the WAP content server upon request. The WAP 1.1 protocol is used for the authorized enquiries, though the authors themselves suggest the use of WAP 1.2 in future to make use of features for event notification.

In [3], Dong and Zhu describe a wireless ECG monitoring architecture that uses Bluetooth for connectivity between an ECG detector and the handheld or PC; and GPRS/Internet for the connection to the hospital server. The ECG detector described is a wearable computer which detects and processes the real time ECG signals. This can then be delivered to the handheld or PC, which in turn connects with a central server.

A framework for wireless communication within a hospital is also given in [6]. Lakas and Shuaib describe a SIP-based architecture including wireless Personal area networks using medical equipment with Zigbee devices that are interconnected through the WLAN infrastructure. The Session Initiation Protocol (SIP) is used to provide event notification and managing or communicating medical tasks. The authors also envisage other extensions including GPRS for communication beyond the hospital walls.

An Electrocardiogram instrument is used by medical physicians to measure the human heartbeat rhythm. This can help determine the medical condition of a patient. Using an ECG instruments involves placing 8 electrodes and one ground electrode on a patient. Typical ECG instruments are standalone devices with a physical user interface and can produce paper recordings. The ECG instrument measures the difference in voltage potential between each of the electrodes. A typical ECG signal frequency range is between DC and 100Hz [1]. Typical measuring speeds of ECG instruments are 500Hz. Twelve standard ECG waveforms are used by medical physicians. However, only 8 waveforms can be measured. The other 4 waveforms can be extrapolated using the measured waveforms.

3. Medical Information System Network

The Medical Information System Network (MISN) consists of Medical Information Nodes (MINs) connected to a central server via an Ethernet network. The MISN structure is shown in Figure 1. Each MIN can be attached to a patient's bed in a hospital ward and is associated with a particular IP address on the hospital network. The ECG instrument is plugged into the MIN when it is needed. Each MIN also has a wireless Bluetooth transceiver which is used to communicate with the mobile computing devices (MCDs). An MCD is used by the medical practitioner to control the MIN. Alternatively, each MIN can also be controlled via a webpage from an authorized

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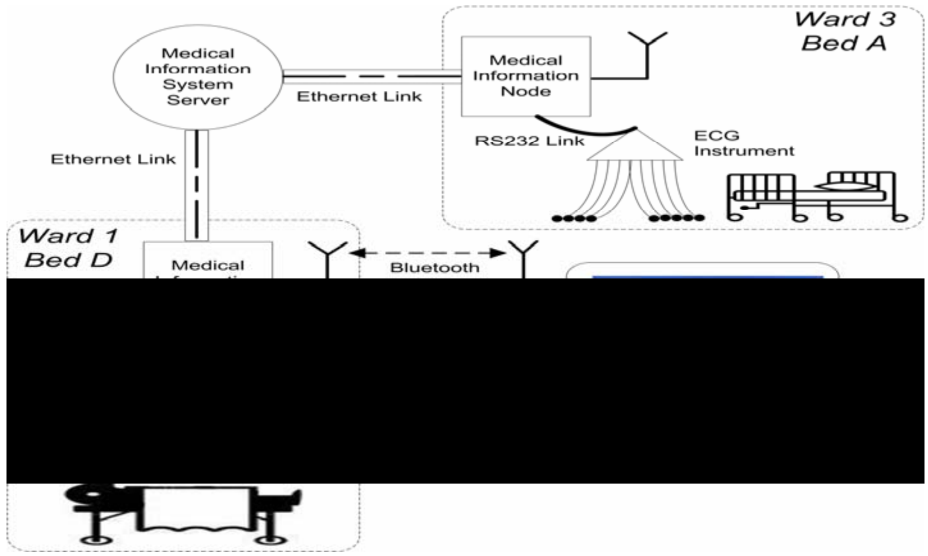

Figure 1 - Structure of Medical Information System Network (MISN)

computer on the network. The central server provides file space for each MIN to store its recordings.

3.1. MCD Client ECG Viewer Program

As mentioned earlier, Bluetooth is used to provide a control link between the mobile device and the MIN. A control communications protocol was developed to allow the mobile device's ECG viewer client program to control the MIN. The control communications protocol is a serial ASCII based protocol that uses the Bluetooth Serial Profile as a transport layer. For security reasons, each MIN's Bluetooth address is recorded in a central database. The client program will only connect to a MIN if it can match the MIN's address in its MIN Bluetooth address database. In the future, the MIN will have access to an MCD Bluetooth address database. This will ensure that the MIN establishes Bluetooth links with authorized MCDs.

The Client ECG viewer program on the MCD sends control protocol commands to the MIN which responds with either the required lead data or the appropriate reply. The eight standard ECG leads can be viewed and recorded by the Client program. The ECG leads are recorded by the MIN and saved as a Comma Separated Value (CSV) file on the server. The ECG leads are also saved in a Scalable Vector Graphics (SVG) file format. The SVG file format allows the ECG leads and patient details to be viewed in a web browser as seen in Figure 2.

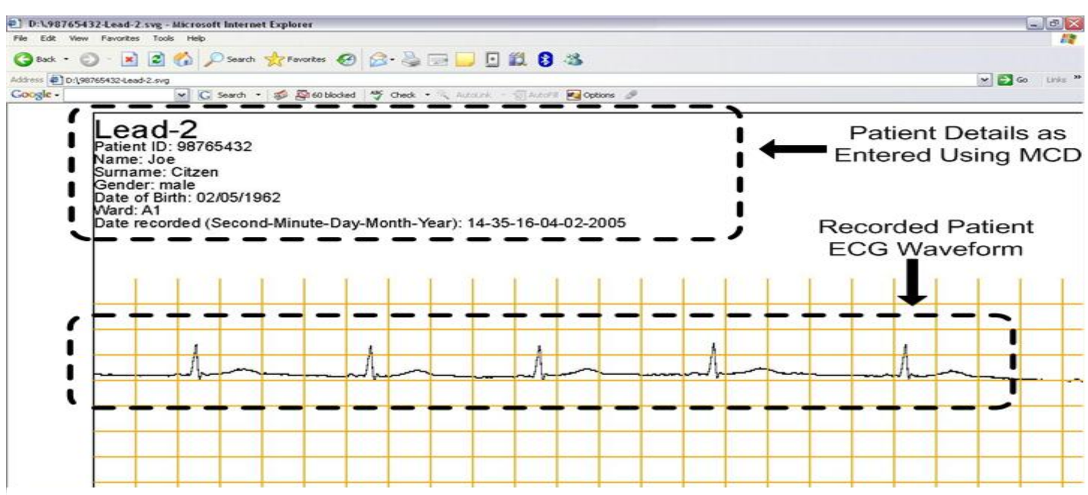

Figure 2 - Patient Record in SVG Format

Figure 3 - Patient Form as Seen on User's MCD

The Client program also prompts the user to enter the minimum patient details required to identify the patient. This includes the patient's name, surname, gender, patient identifier number, ward and bed identifier. The patient detail form and ECG lead waveform can be seen in Figure 3 and Figure 1.

3.2. Web-Page Interface and File Storage

As seen in Figure 1, the MIN is connected to the central server via an Ethernet network. The MIN functions as a HTTP web-server which allows it to host webpages. The MIN has a series of webpages that allows the ECG instrument lead outputs to be viewed. Each webpage consists of a Common Gateway Interface (CGI) script that controls the ECG instrument to translate and display the ECG lead data. Figure 4 shows how a typical Lead I and Lead II output is viewed using the Webpage interface. The MIS server is able to access a particular MIN's ECG lead webpage by using the MIN's IP address. The MIN uses the uClinux Network File System (NFS) as its file system. Thus it is able to remote mount a folder on the server over the network. The MIN stores the recorded ECG data in CSV and SVG formats in its designated folder on the server.

4. Medical Information Node (MIN) Implementation Overview

The Medical Information Node is implemented on a Xilinx Spartan 3 FPGA. The architecture of the MIN can be seen in Figure 5. The MIN's architecture consists of a 32bit Microblaze softcore processor, serial UART, General Purpose Input Output (GPIO) and the ECQ Acquisition Module. An external Ethernet MAC controller and external SDRAM memory devices are connected to the Microblaze processor. The Microblaze processor's on chip peripheral bus (OPB) is used to connect the serial UART, ECG Acquisition Module and the LED indicator output to the Microblaze processor.

4.1. Bluetooth Link Interface

A Bluetooth Serial Port module is used to facilitate the Bluetooth link between the MIN and the mobile device. The Bluetooth Serial Port Module is a separate device to the FPGA that functions as a Bluetooth serial port as specified by the Bluetooth

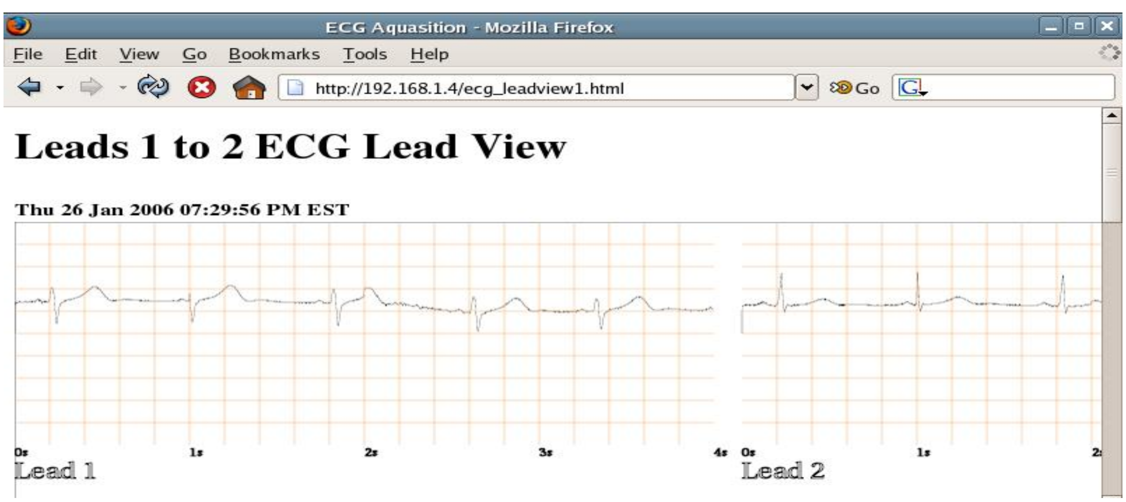

Figure 4 - MIN Webpage Interface Showing ECG leads

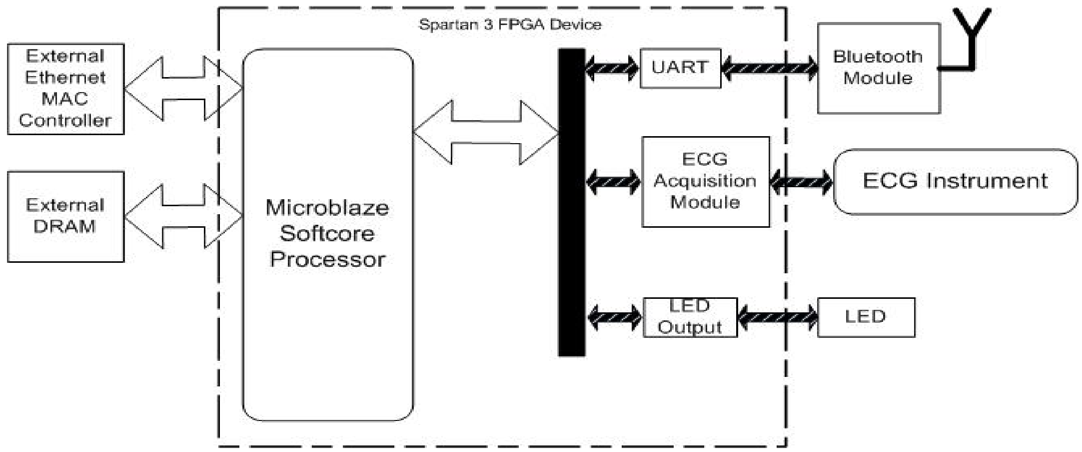

Figure 5 - Digital Architecture of Medical Information Node (MIN)

Serial Port Profile Specification. It is controlled by the Bluetooth controller process through a serial UART. The Bluetooth controller program is a uClinux software process that executes on the Microblaze processor and controls the Bluetooth Module by using manufacturer specific AT commands. The Bluetooth controller process responds to the control protocol commands received from the mobile device's client program.

4.2. Ethernet Link Interface

An external Ethernet MAC controller is used to connect the MIN to an Ethernet network. The Ethernet MAC controller is interfaced to the Microblaze processor using its standard external memory controller module. The Microblaze processor's EMC module allows devices that require a high speed interface to be connected to the Register Address Space of the Microblaze processor. As mentioned before, the MIN functions as a web server. When the MIN's webpage is accessed through a web browser, the Web Controller uClinux process is activated. The web controller starts the ECG instrument and displays the ECG lead data on the Webpage.

4.3. ECG Acquisition Module

The ECG acquisition module is used to control the ECG instrument. The ECG instrument accepts commands and transmits ECG lead data using a serial UART based protocol. The ECG acquisition module is implemented as a custom digital logic module on the FPGA and the architecture can be seen in Figure 6. The ECG acquisition module consists of a UART module, ECG Instrument control module, ECG Lead Data Integrity module, ECG Lead Data memory and Control Interface module. The digital resources required by this module are discussed in Section 5.

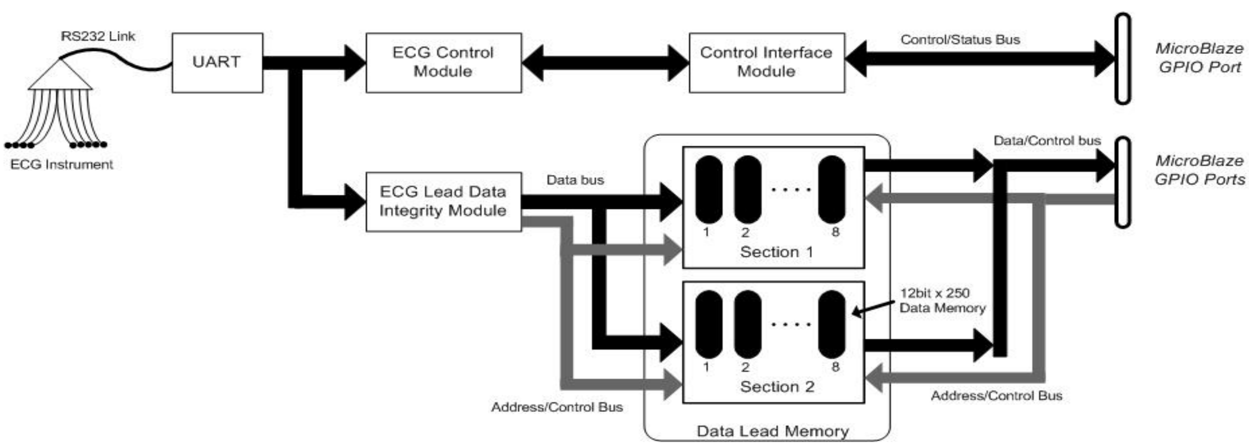

Figure 6 - Digital Architecture of ECG Acquisition Module

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4.4. ECG Control Module

The ECG Control Module transmits ASCII-based control commands via the UART module to the ECG Instrument. The commands control which lead(s) are to be sampled, when to start and stop sampling and when to turn the ECG Instrument on and off. The ECG control module is implemented as a typical finite state machine.

4.5. ECG Lead Data Integrity Module

The ECG Lead Data Integrity module is used to receive, check, extract and store the ECG lead data from the incoming ECG lead datagram packet. Each lead datagram packet contains one sample of each selected ECG leads. Each data sample received is 12 bits long. A datagram packet is received every 2ms. Once the datagram packet has been received via the UART module, a checksum is calculated and compared to the received datagram's checksum. If the checksums match, each selected lead 12bit data sample is extracted and stored in the ECG lead data memory. If the checksums do not match, the datagram is discarded.

4.6. ECG Lead Data Memory

The ECG lead Data memory is used to store the received ECG lead data values from the ECG lead data Integrity module. As seen in Figure 6, the data memory is split into two main sections with each section containing eight memory modules. Each memory module is 12bits wide and can store up to 250 ECG samples. Eight memory modules are used to store the maximum amount of ECG lead data that can be extracted from one datagram packet. This is because only eight ECG leads are sampled by the ECG instrument. Each memory module stores 250 ECG samples, which is the number of samples received in 0.5s from the ECG instrument.

The memory sections are used sequentially by the ECG lead Data memory. When section 1 has been fully filled, it signals the Web or Bluetooth controller process, via its GPIO ports, to read the ECG lead data. While section 1 is being read, section 2 is then used to store the received ECG lead data. The memory sections are used sequentially, to ensure that there are no delays in storing and accessing ECG lead data. As seen in Figure 6 the ECG lead data memory's address and data buses are connected to two GPIO ports on the Microblaze processor's on chip peripheral bus (OPB).

4.7. Control Interface Module

The control Interface module is used to allow the Web and Bluetooth controller processes to command the ECG acquisition module to initiate the ECG signal sampling. The control interface module also alerts the web and Bluetooth controllers when ECG lead data can be accessed form the ECG lead data memory. As seen in Figure 6, the control module is connected to GPIO ports on the Microblaze processor's OPB. The Web and Bluetooth controller processes use a GPIO uClinux driver process to read and access the port.

5. Resource Usage Comparison

This section discuses the amount of digital, processing and power resources used by the MIN. The processing and power recourses used to implement the ECG acquisition module as a digital logic module is compared to that required to implement it as a software uClinux process.

5.1. Digital Resources Usage

Table 1 shows the amount of resources used by the main digital modules of the MIN. The digital resources are measured in Complex logic Blocks (CLB) slices, Flip Flops (FF) and block RAM (BRAM). The Spartan 3 XC3S1000 FPGA was used to implement the MIN. Table 1 also shows the percentage of the Spartan 3 XC3S1000 used by the entire MIN implementation. The Microblaze processor uses the most amounts of logic and BRAM. In comparison, the ECG acquisition module's logic usage is quite small. The BRAM usage of the ECG acquisition module is mainly for the ECG data memory module. The Microblaze processor does not have its data and instruction caches enabled. This was done to ensure there would be enough BRAM modules that can be used by the ECG acquisition module.

Table 1 - Digital Resource Usage

	ECG Acquisition Module	Microblaze	Total Spartan 3 XC3S1000 Usage (%)
CLB	436	2400	36.93
FF	613	3159	17.79
BRAM	4	15	79.17

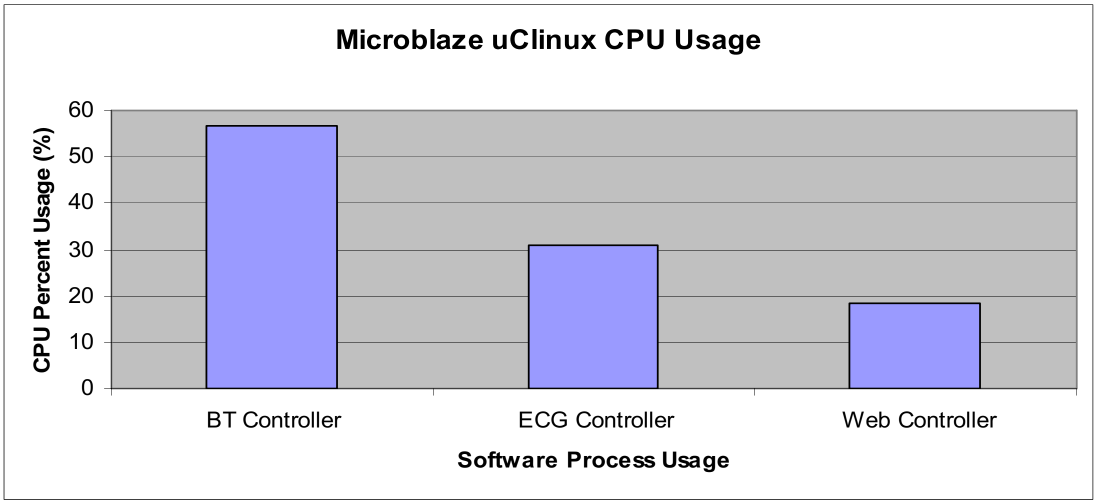

Figure 7 - Microblaze CPU Usage Comparison

5.2. Processing Usage

This section discusses the central processing usage of the Microblaze processor running the uClinux Operating system. The Microblaze processor has a 16MHz clock speed. Figure 7 shows the percent usage of the three most active uClinux processes. The ECG controller process implements the function of the ECG Acquisition controller, in software. As shown in Figure 7, the Bluetooth controller process has the highest CPU usage. This is due to the Bluetooth controller process being more active than the other controller processes. The Bluetooth controller process not only has to access the ECG lead data but it has to transmit the ECG lead data to the MCD via the Bluetooth module. The Bluetooth controller process also continuously monitors the Bluetooth module for incoming connections and control protocol commands from the MCD's client program. The Bluetooth controller process also has a higher memory usage and therefore access the external memory more often than the other processes. This is because the Bluetooth controller process requires memory buffers to store the ECG lead data before transmitting it to the MCD's client program.

5.3. Power Usage

The highest power usage of the MIN occurs during its three processing modes. The processing modes are:

1) *Bluetooth Interface* – Transmitting lead data through Bluetooth.

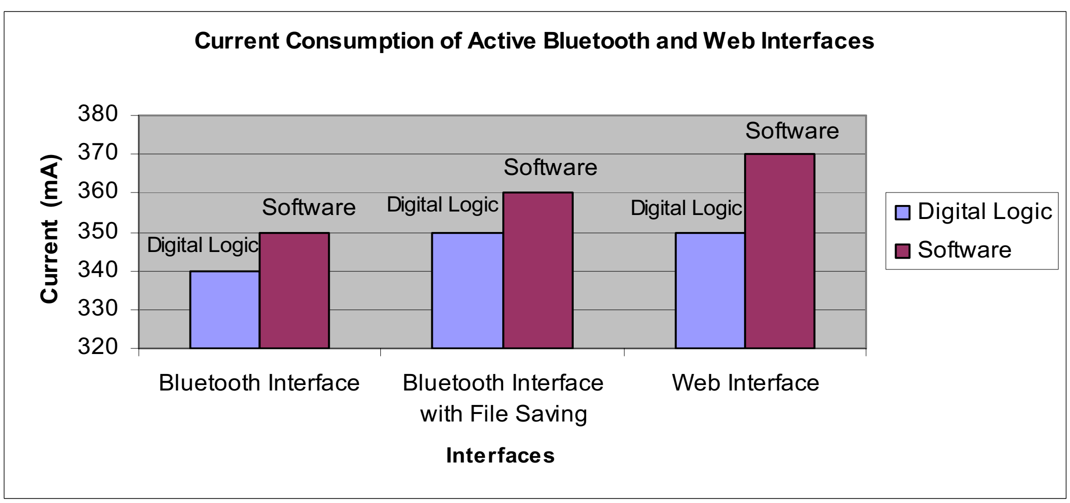

Figure 8 - MIN Current Consumption Comparison

2) *Bluetooth Interface with File Saving* – Transmitting lead data through Bluetooth and saving lead data on MIS server.
3) *Web Interface* – Displaying lead data graphs in Web browser.

Figure 8 shows the current consumption of the MIN during each of the three processing modes. A comparison of using a digital logic and software implementation of the ECG acquisition module is also shown in Figure 8. The highest power consumption occurs during mode 3. This is due to the current usage of the external MAC controller. One would expect mode 2 to be the highest. This is not the case even though the external MAC controller is being used. This is because the data rate of the file transfer is lower than the data rate used in mode 3.

In all modes, using the digital logic implementation of the ECG acquisition module results in a lower current consumption. This could be due to the fact that the software version of the ECG acquisition module has large memory buffers to store the ECG lead data. This means it has to access the external memory often. The external memory accesses cause the current consumption to rise.

6. Conclusions and Further Work

In this paper we have presented an integrated networked ECG monitoring system that uses mobile computing devices and webpages as control interfaces. The MISN consists of medical information nodes (MINs) connected to a central server. Each MIN can be controlled by the Client ECG viewer on a mobile computing device via a Bluetooth connection. The MIN was designed to allow the output of an ECG instrument to be viewed using a mobile device or web browser and to record the ECG instrument's output into a file that is saved on a central server. The ECG recording of a patient is saved in both CSV and SVG formats. This allows the recording to be easily viewed in common spreadsheet programs and web browsers.

The MIN consists of a 32bit Microblaze softcore processor and custom logic modules that is implemented on a Xilinx Spartan 3 FPGA. The Microblaze processor runs the uClinux operating Systems. The most time critical function of the MIN was the ECG acquisition module. The MIN design implementation was found to occupy a smaller percentage of the Microblaze's CPU time and also consume less current when the ECG acquisition module was implemented as custom digital logic rather than as a software process.

The main advantage of the MISN is that it allows an ECG instrument to be networked. This has the logistical advantage of being able to organize the ECG Instrument's output in a patient database which can be easily accessed. The advantage of using an FPGA for this application was that time critical functions such as interfacing to the ECG instrument could be implemented as digital logic rather than as a software process. The use of Microblaze and uClinux has the advantage of being able to interface the MIN to an existing Ethernet network. Another advantage is the use of existing open source code for web and network connectivity functions.

Further work envisaged for this includes the expansion of the Medical Information Nodes to interface to a variety of medical instrumentation devices. Further wireless connectivity could be achieved, by converting each MIN into a Wifi embedded node. This would eliminate the need to install Ethernet cabling throughout hospital wards and replace the wired contact with the server.

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